

FCPA/PPD/CD review of CCD R&D

March 24, 2009

Attendance

Reviewers: Craig Hogan, Dan Bauer, Chris Stoughton, Hogan Nguyen

Representing PPD: Mike Lindgren, Peter Wilson

Representing CD: Bob Tschirhart

Attending by video: Darren Depoy (TAMU)

Goals of the review

1. Determine the technical progress of the two teams involved with low-noise CCDs
2. Assess the need for continued resources from the existing DOE grant (Lab 08/07), and from within Fermilab (FCPA, PPD and CD).
3. Determine possible science applications for these devices and assess the possible fit of this science with the FCPA program

Recommendations

1. We encourage the teams to continue their R&D towards low-noise CCDs to the point of demonstration the usefulness of these devices for physics. Advancing beyond that will require an additional review within the laboratory, and prospects for external funding. The pace of R&D work should not grow to the point where it significantly affects the progress of the DES project.
2. If the JDEM design changes again, and incorporates many more CCDs, Fermilab should consider a substantial role in packaging and testing.
3. The goal for astronomy should be readout that contributes no more than 0.5 electrons noise in a prototype CCD that could be mounted on a spectrometer and tested at a telescope, in conjunction with university observers. The science goal would be a demonstration of spectra from very faint objects that cannot be obtained with present cameras. This is within the mission of FCPA and we believe the resources available from the DOE grant should be used for this purpose.
4. The goal for dark matter uses should be a demonstration that a properly shielded low-noise CCD achieves a background rate of about 1 event/keV/kg/d for electron equivalent recoil energies in the 100-1000 eV range. Since the intrinsic background of the mounted CCDs is not known yet, it is hard to assess whether this goal can be achieved. However, the payoff would be a significant improvement in searches for very low mass dark matter particles. Continued R&D funding should be made available from FCPA/PPD/CD at approximately the current level to determine if this technology can produce such physics.

Notes from Individual Reviewers

Dan Bauer

Tom described the history of these efforts. They sprang from the DES packaging and testing efforts for LBNL CCDs that have high quantum efficiency in the red ($>90\%$ at 9000 Å). The DES effort has developed a substantial infrastructure at SiDet, with ESD safe clean rooms, an assembly area in Lab C and testing facilities in Lab A.

It was assumed that this infrastructure would become a major bonus for SNAP, which was supposed to have 36 LBNL $3k \times 3k$ CCDs. There was an MOU with LBNL in 2005 for development of the testing and readout scheme for these CCDs. Further infrastructure was developed over the next 3 years and Tom obtained a grant of \$435K from the DOE (LAB 08-07) in June 2008 to continue the design work for what had now become JDEM. The grant was supposed to cover a mechanical tech, 117K M&S, 75K to Yale, as well as travel, training and documentation. Work started October 1, 2008, with real progress late in the fall. They completed one working package, although it was not space qualified. To date, 29% of the labor has been used, but only \$5.3K M&S. Recently, the JDEM design has evolved and currently contains only 9 LBNL CCDs. Given the reduced size, LBNL may choose to do packaging and testing without FNAL participation. Tom indicated that Kathy Turner has given permission to use the rest of the grant money towards low noise CCD readout.

Meanwhile, Tom, Juan Estrada and Gustavo Cancelo have been working on a low noise readout scheme for these CCDs. The intent was to achieve <0.5 electrons readout noise. At that level, there are interesting applications in both astronomy (spectroscopy and narrow band imaging where photons are scarce and S/N a problem) and in low-mass WIMP searches (arxiv 0802.2872)

For CCD spectroscopy, the counts/pixel are proportional to imaging time, photon flux, dark current, and readout noise. The current state of the art for cooled CCDs is 5-20 electrons/pixel/hour for fast readout and 2 electrons/pixel/hour in slow readout mode (50 kpixels/sec). Improvements in signal to noise achieves the same as increasing the aperture of the telescope for applications that are 'photon-starved' like spectroscopy of faint objects. Gustavo Cancelo described digital signal processing techniques that show promise for reducing this to 0.5 electrons/pixel/hour or lower.

For low mass dark matter searches, CCDs of the type used for DES provide significant mass (currently about 2 gram) and very low energy thresholds. It seems feasible to achieve an RMS noise of 7.2 eV in ionization energy, which corresponds to 0.036 keVee. Large dark matter experiments typically are not able to measure recoil energies less than about 1 keV. However, to achieve decent limits on the WIMP-nucleon cross section, any such experiment must have very low backgrounds. Juan showed that the CCDs can be used to reject penetrating particles that leave tracks, but there is still a significant background from low energy particles. With current shielding, the background is roughly 10000 events/keV/kg/day. Better shielding should reduce this by at least $\times 100$, but the intrinsic background of the CCDs and packaging is not yet known.

Chris Stoughton

I am enthusiastic about the application of this technique in optical astronomy and dark matter searches.

1. I am concerned about continuing support for SNAP/JDEM CCD packaging. Tom presented a good plan to close out the effort and document the process. However, there are questions about what the SNAP/JDEM project expects from us. This mission will benefit from more CCDs in the focal plane. I would like us to work to avoid any perception -- real or imagined -- that FNAL will not be able to support the R&D to enable this.
2. Juan's strategy to push the low-mass detection limit for direct detection of dark matter is sound. "Reasonable" theoretical models do not predict that WIMPS will have this low mass, but we should not let that deter the search! The modest investment in the read-noise R&D is worth it.
3. Optical astronomy has interesting niches for zero read-noise CCD read out. Current research projects in the FCPA require faint-object spectroscopy. Demonstrating the electronics with these objects is a natural progression.
4. Once the technique is demonstrated -- in the lab, in DM searches, and at telescopes -- it will be "easy" to find instrumentation projects at observatories that would benefit from it. It is reasonable to expect that these projects would be able to fund production development.
5. My suggestions for follow-up work are:
 - a) clarify our collaboration with JDEM/SNAP and their expectations. Keep DOE project office well-informed of how the grant money is spent.
 - b) develop the electronics for the DM searches.
 - c) develop a specific plan and budget for deploying a prototype at a telescope
 - d) do an initial survey of potential customers for these read out electronics
 - e) understand the IP issues, and whether getting a formal patent is in order.

Craig Hogan

-as a dark matter technology, it is very early stage but potentially promising and Juan is following an interesting new direction. It is a fantastic story of FCPA synergy between our different directions.

-for astronomy, the low read noise is potentially transformative for photon-starved (high resolution, faint object) spectroscopy. There are lab- appropriate problems where this is important (QSO absorption lines, supernovae) although we aren't pursuing that kind of astronomy now. A worthy and realistic goal is to find a way to export the technology into the astronomy community where it will be supported and used. This should be done in concert with an instrument-savvy institution such as Carnegie or NOAO.

Hogan Nguyen

- I was impressed with all the talks. The CCD technology is quite important for the particle astronomy community. The mastery of the CCD technology and the technological achievement shown by the DEcam team is impressive.

- Developing a lower noise CCD readout system is a very interesting idea and is perhaps worth pursuing. Reducing the noise effectively increases the telescope size and/or reduces the integration time. An example application given is the Lyman-alpha absorption spectra at very high red shifts. Current state-of-the art CCD experiments reach 2-3 electrons of noise.

Gustavo and Juan discussed the very real possibility that the noise can be reduced well below 1 electron, which would be an amazing achievement. Initial results from Gustavo appear to be very promising. Gustavo should be encouraged to complete these studies.

If the in-lab results continue to be promising, the proponents discussed mounting such a device onto another telescope. The scope of this work should be understood, as it represents potential commitment of new readout hardware and expertise.

- Using CCD's to detect low mass wimps, and perhaps coherent neutrino scattering, is also scientifically interesting. However, it wasn't clear to me the level of radiopurity needed to turn DAMIC into competitive experiment for low mass wimps or coherent neutrino scattering. From the transparencies, I couldn't tell whether the prospectus results assumed additional radio purification.

As Dan knows, radio-purity requirements would really increase the complexity of the experiment. Radio-purity experts do exist at the lab, and should be consulted if necessary.

- Both of these efforts are currently very modest, and do not use any (significant) mechanical engineering, which is in very short supply at the lab.

- If the application of CCD's to other projects (beyond DEC/JDEM) is encouraged to continue at the lab, the proponents should continue to discuss with PPD regarding the facility space and staff needed for CCD work. The Sidet staff does need to plan, for example, for the CMS silicon upgrade.

Bob Tschirhart

The Computing Division recognizes the technical significance of the estimator-based techniques to minimize CCD readout noise and will continue to work toward demonstrating and publishing a "proof of principle" of these techniques. Committing effort beyond this demonstration phase will depend on prioritization guidance from the directorate and the balancing of other activities.

Email from Darren Depoy

Dear Tom, Juan, and Brenna --

You recently described work being done on creating CCD systems with extremely low read noise. This is a very exciting development, particularly if the noise can be reduced to below one electron. This level of noise would allow an increase in signal-to-noise equivalent to a correspondingly larger telescope primary diameter for certain types of observations. For example, decreasing the noise from typical values of 3-5 electrons to <1 electron would allow a 4m-class telescope to perform as well as or better than a 10m-class telescope.

Such an improvement in a DECam-like CCD, coupled to the exceptional quantum efficiency in the far-red of those devices, would permit observations of a wide range of targets of interest to dark energy studies. For example, installed in a high resolution spectrometer such a system could be used to observe faint Ly-alpha absorption lines along the line of sight to very distant galaxies or quasars, which can be used to measure the mass power spectrum in the Universe. Such a CCD system could also be used to obtain spectra of almost any other interesting target: type Ia supernovae at high redshift, lensed arcs of strong gravitational lenses, and standard distance ladder calibrators.

A field test of such a low-noise CCD system would be very valuable, particularly if the device is a 2Kx4K device in a picture frame package.

I have a spectrometer that can accommodate this sort of CCD and I can arrange for telescope time for test observations.